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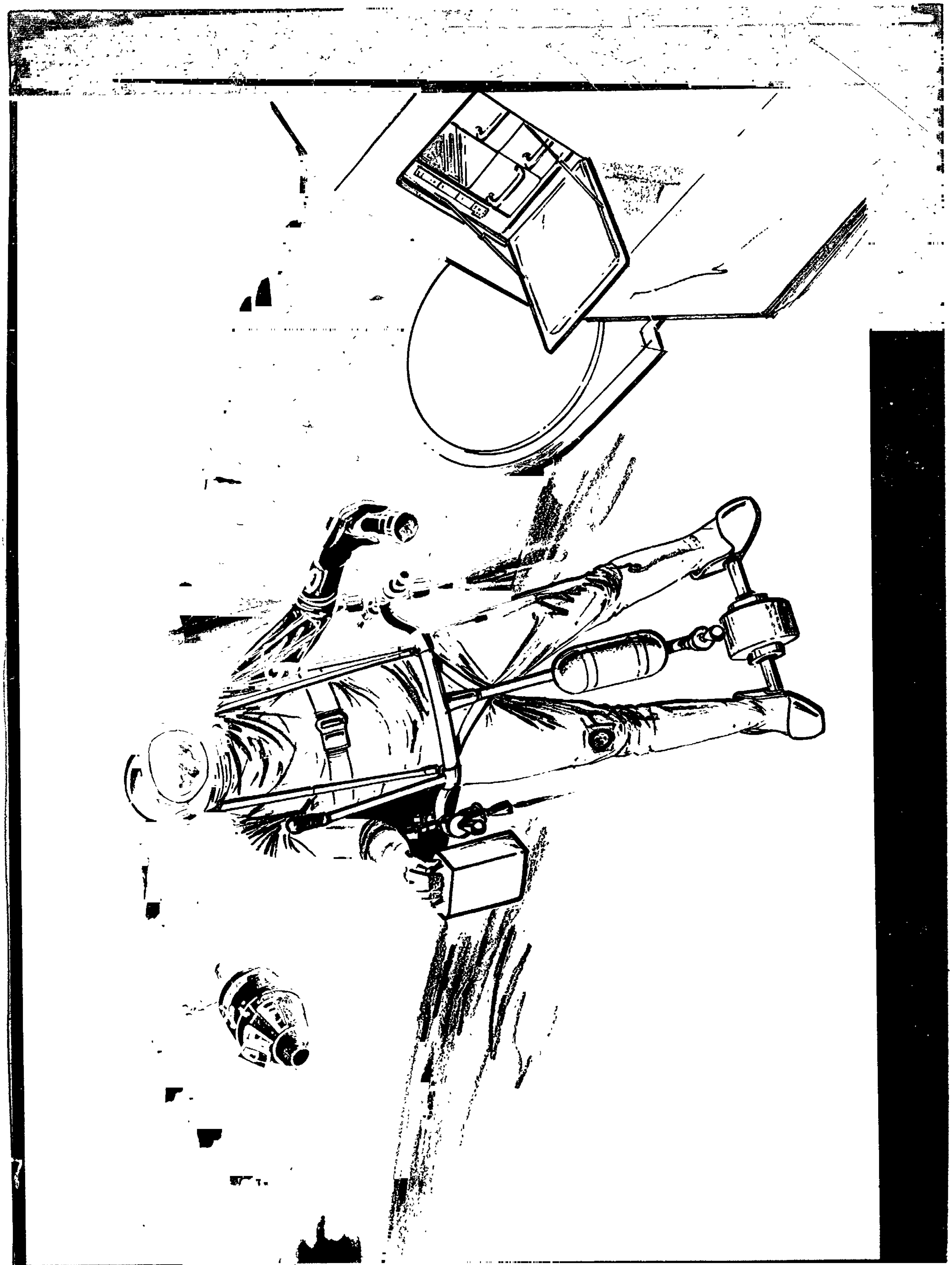

Grumman Research Department Report RE-275

HANDS-FREE, PRECISION CONTROL FOR EVA — AN EXPLORATORY STUDY

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PREFACE

The work described in this document, except for the development of the research facility, was a portion of a study performed by the Research Department of Grumman Ai. raft Engineering Corporation under NASA Contract NAS 2-2595, entitled "Research into the Use of the Human Balancing Reflex for Stabilization and Control of Vehicles in One-g and Sub-g Environments." The NASA technical monitor was Mr. Melvin Sadoff of the Ames Research Center, Moffett Field, California.

ACKNOWLEDGMENT

The authors wish to acknowledge with gratitude the large contributions to the research effort summarized here of Mr. John Wagner, who designed the research tool and supervised both its operation and numerous modifications, Mr. Edwin Knoflicek and his team of technicians, who built the device and kept it running, Mr. Gerard Layman, who did the prototype system preliminary design, and Mr. Edward Seckel of Aeronautical Research Associates of Princeton, Inc., who contributed valuable consultation.

SUMMARY

Extensive research into the use of the human foot-balancing reflex for control of vehicles in the one-g environment has led to an extrapolation of the concept to its use for Extra Vehicular Activity (EVA), the maneuvering of free-floating spacemen. An exploratory program in which zero-gravity was simulated for three degrees of freedom in the horizontal plane has proved the basic utility of the idea and provided a model for the preliminary design of a prototype, EVA control system.

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BACKGROUND

The use of the human balancing reflex for vehicular control was publicly propounded by Charles Zimmerman of the NACA in the early 1950's. His central thesis was that the learned pattern of reflexes used by a person in standing is essentially the same as that required to balance a force-vector supported platform, and hence should be directly applicable to the control of hovering type vehicles. This concept and its simple but dramatic demonstration by Zimmerman (Ref. 1) piqued the imagination of a great many aeronautical engineers and led shortly to several experiments with free-flying platforms of various sorts. There were, for example, the ducted-fan machine of Hiller (Ref. 2), the stand-on helicopter of DeLackner (the "Aerocycle" tested by Princeton University, Ref. 3), and several research-oriented devices built by the NACA (Refs. 4 and 5).

Since that initial period of activity, engineering interest has waned, probably for lack of definitive information on optimum usage of the human balancing reflex, and the concept has made only sporadic appearances in one or another embodiment; for example, the "lunar scooter" studied by North American (Ref. 6), and the "Jet-Shoes" developed by NASA - Langley (Refs. 7 and 8). Grumman Research, however, has maintained a constant enthusiasm for the concept and has kept a small but steady effort going in the study of its application to various classes of vehicle and its significance to the fundamental understanding of human vehicular control behavior. This work, partially supported by the NASA, is described in Refs. 9 through 12.

A fairly extensive discussion of the advantages and potential applications of the balancing-reflex concept is given in the appendix (abstracted from Ref. 9). Of the items mentioned there, probably the most timely is the application of the balance-reflex concept to propulsion and control of the free-floating spaceman.

The difficulties encountered by a spaceman in attempting to do any significant amount of useful work outside his vehicle are by now well documented; they clearly stem from his inability to establish and maintain a required orientation of his body with respect to a "target" object without resorting to the use of clumsy restraining devices, dexterity preempting hand holds, and debilitating body contortions. Clearly, what the spaceman needs is a reasonably powerful and delicate means of controlling his body orientation that neither encumbers his hands nor requires him to fight his unyielding pressure suit. Adaptation of the natural, body-orienting responses of the feet and legs to the modulation of appropriately located thrusters appears to be a way to provide this means reliably, cheaply, and simply. The present document describes some preliminary work in this direction.

CHRONOLOGY OF THE DEVELOPMENT OF A SYSTEM

The development of a system for adapting the natural, neuromuscular, body-orienting responses to control body-orienting thrusters for spacemen is, almost by definition, exploratory and experimental in nature. The particular problems and pitfalls likely to be encountered cannot be predicted, and so the work must proceed in a stepwise manner, each step directed by the experience obtained from the preceding ones. The following discussion is a chronology of the steps that have led, in the present case, to a workable EVA control configuration and a preliminary prototype design.

The Simulator

Since it is not practical to do developmental work of the sort described above in the real environment, some sort of simulation becomes necessary. Many ways of simulating zero-g have been used or suggested, but of course all have drawbacks of one kind or another. Water immersion, for example, produces large viscous forces and is not completely free of gravity effects. Cable suspension becomes involved with complicated pendulum dynamics. And so forth.

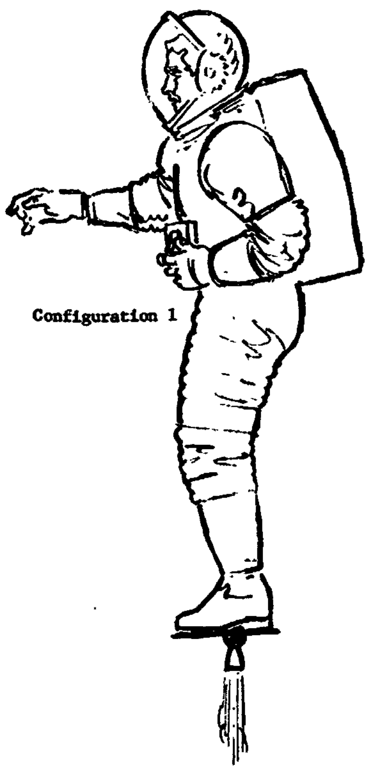
For the resources at hand, the most practical compromise with reality appeared to be a three-degree-of-freedom simulation based on frictionless motion in the horizontal plane. The particular combination of degrees of freedom obtainable in a plane (two translations and one rotation) is reasonably defensible for exploratory work in zero-g simulation. It does provide a logical sort of consistency, a representation of the complete job of "getting around" in space (albeit two-space rather than three).

Of the three possible configurations for planar motion of the human body, the one involving pitch rotation (see Fig. 1) appeared to be the most appropriate for initial exploration. Thus the simulator or "scooter," as it came to be called, took the form of an articulated bed, carried by two, levapad (air-bearing) supported tripods, upon which a person reclines. Although designed primarily to accommodate a man lying on his side as shown in Fig. 2, the device can be adapted readily to the supine position. The special floor on which the scooter glides is made of epoxy plastic poured over a concrete base, and is about 30 feet square, a more-or-less arbitrary compromise between desirability, availability, and expense.

In all of the exploratory work carried out to date using the zero-g simulator, the experimenters have served as the primary flyers and evaluators. Numerous others, including experienced pilots, however, have flown the scooter in various control configurations, and their impressions of its behavior coincide generally with those expressed in the following sections. No astronauts have as yet participated.

The Original Control Configuration

The one-g, balancing-reflex concept, in its most elemental form, makes use of a single, supporting thruster which, with the aid of gravity, gives the flyer control of five degrees of freedom. It is the very essence of elegant simplicity. Thus it is not at all surprising that extrapolation of the idea to zero-g applications should center on basically the same configuration. This was in fact the case for the initial effort at Grumman, and the idea still prevails in the NASA Jet-Shoes work (Refs. 7 and 8).


Configuration 1

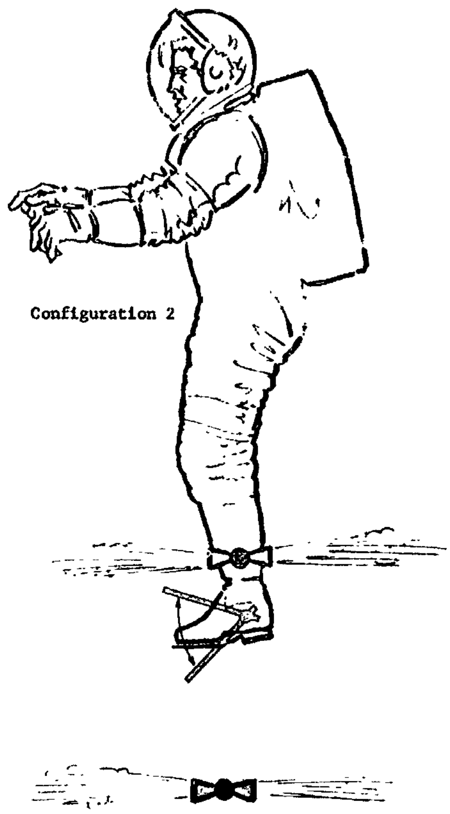
Unfortunately, the very first simulator trials demonstrated quite clearly that the simple configuration could not provide what the Grumman research philosophy had established as a design goal: natural (unconscious), precise control of the body in space. An immediate and clear symptom of the problem was a complete absence of any feeling of "balancing," in the automatic sense which is typical of one-g jet-platform flying. Consequently there was no delicacy of control. The reasons for this (obvious in retrospect) also became quite clear. First, the amount of thrust needed for fairly spirited maneuvers was very small (less than five pounds), hence the system gain, i.e., angular acceleration per degree of ankle deflection, was extremely low, orders of magnitude below the optimum for one-g balancing (as established by Ref. 9). Second, thrust was required only for brief periods, hence pitching responses did not inexorably follow ankle motions, as in the one-g jet platform, and there could be no sustained "feel" of the system.

Besides the basic balancing problem demonstrated by the brief series of experiments with the jet-platform configuration, a more subtle difficulty began to come to light. The original thinking had been that, in the absence of gravity combining vectorially with thrust for forward motion ("walking" mode), translations would be accomplished primarily in a "swimming" mode (head or feet first), with up-and-down thrust controlled by knee flexing. It began to be apparent, however, that people have a natural inhibition against traveling any distance head-first or feet-first; a flyer insists that he must be able to look in the direction of motion, and if he cannot, as when he is inside a space suit, he becomes not only apprehensive, but faulty in his judgement of direction and speed. This phenomenon might have something to do with the well known "steep hill" or "dive angle" illusion, in which even an experienced skier or pilot misjudges his angle of descent, often by a factor of two, a 30° slope, for example, being interpreted as 60°, and a 60° slope as "vertical."

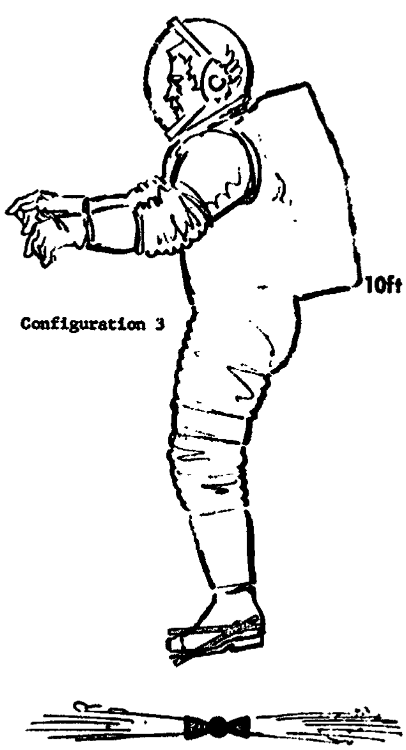
In light of the clear and inescapable conclusion regarding adherence to the Grumman objectives, some commentary on the apparent success of the Jet-Shoes concept (Refs. 7 and 8) is in order. As far as can be determined, the NASA personnel have adopted a quite different, but equally valid, set of ground rules. They, too, appear to have uncovered the same basic problem early in their experimentation, but they have chosen to sacrifice the high degree of control finesse inherent in natural balancing in favor of the extreme simplicity of Jet-Shoes. Their objective has become simply to provide the spaceman with a cheap and reasonably effective way of getting from one place to another, not to give him precision control when he gets there. As far as is known, they have not concerned themselves with the swimming-mode visual problem.

Control Configurations Two and Three

Following such abject but eye-opening failure of the simple concept to behave in zero-g even vaguely according to objectives, a certain amount of back-tracking seemed to be necessary. The thinking had been along the lines that the simple jet, somewhat elaborated, might serve the complete control and propulsion function, as it does in one-g. It now appeared, however, that control of the various degrees of freedom would have to be separated and, perforce, evaluated one at a time. Pitch control, which is the most closely associated with balancing, seemed to be the appropriate function to look at first, and the scooter was therefore reworked to provide for a pair of crosswise (fore-and-aft) thrusters, located near the feet, and controlled, roughly proportionally, by a three-port modified ball valve actuated mechanically by ankle deflection. Photographs of the configuration are shown in Fig. 3.



Configuration 2



Configuration 3

The previous experiments had clearly brought out the need for higher system gain, but just how high it should be was moot. For one-g flight Ref. 9 had established an optimum gain in the vicinity of .1 g acceleration at the feet per degree of ankle deflection, but conceivably this value might not be in any way related to the requirement for zero-g flights. A simple side experiment using the research apparatus of Ref. 11, suitably modified (Fig. 4), indicated that the .1 g per degree value was probably valid. It turned out, however, that achievement of this value on the zero-g simulator, without the introduction of inordinate amounts of friction and backlash, was almost impossible. Therefore a compromise value of about .01 g per degree was set up. Results were encouraging; a feeling of balancing, though weak, was now clearly evident. But it was also evident that the gain was still far from satisfactory, and that there was a maneuvering problem in which the unbalanced forces produced by the thrusters during moderate rotational maneuvers built up a disconcerting spurious translation.

The lessons learned from the second configuration led to trial of Configuration 3 in which the single force was replaced by a couple, and the system gain was quadrupled by increasing the thruster moment arm and altering the control-valve linkage. The results of these changes, measured in terms of prior experience, were spectacular; pitch attitude control became entirely natural and effortless, permitting angular displacements to be made with precision, and "tumble" recoveries to be executed smartly. Roll control, briefly investigated with the flyer lying on his back, looked equally good.

Basic faults in the system (friction and dead zone in the linkage), however, had been increased by the gain-changing alterations, and the dramatic elimination of other faults now caused these to stand out very clearly, especially dead zone, which had never really been encountered before in any of the one-g balancing experiments of Refs. 9 and 11.

The Fourth Control Configuration

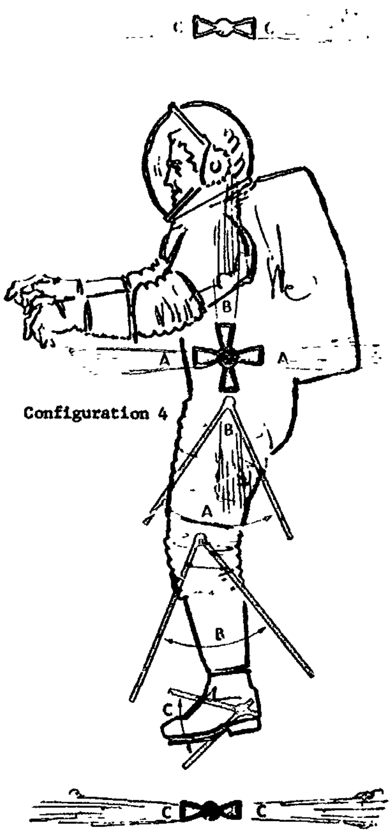
With the encouraging results achieved for pitch control alone, it seemed appropriate to turn attention to the two translational degrees of freedom: fore-and-aft and up-and-down.

There has been general agreement, dating back to the one-g jet platform work of Ref. 9, that "squatting" might be an appropriate mechanism for control of up-and-down thrust. Here, upward acceleration would be the natural and expected response to extension of the legs, and downward acceleration to retraction; the proper direction of response is clear and unambiguous. There is, however, a question about how the body deflection should be measured for transferral to a thruster control valve. The simplest arrangement seemed to be to pick up knee flexing at the appropriate joint in the simulator bed.

In an analogous fashion, waist-bending appeared to be an appropriate mechanism for the control of fore-and-aft thrust, but in this case the choice of direction of the response depends strongly on one's point of view. If one thinks in terms of leaning the upper body (buttocks fixed to the ground), then forward bending should produce forward motion. But if one adopts a "baby-walker" point of view in which the feet are fixed to the ground and the torso is propelled back and forth by the legs, then backward bending (backward thrust of the legs) should produce forward motion. The former arrangement seems to have a more elemental psychological appeal, and certain forms of human behavior can be pointed to in its support, e.g., the tendency of a highly involved observer of some action to "urge" an object toward a desired goal by leaning. The latter arrangement, on the other hand, is an exact analog of the clear-cut, vertical motion case, where the legs also propel the torso in the desired direction.

This philosophical controversy is perhaps resolved by considering that even in the baby-walker case the motion that <u>initiates</u> an action is a lean in the desired direction. It is this unconscious, precursor type of muscular response that would be expected to provide the most natural mechanism for control of the body. For Configuration 4, then, the body-lean philosophy was adopted. Waist flexure, measured between the thigh and torso, was picked up for transferral to the air valve mechanism by a lever extending between the upper and lower halves of the simulator bed. A system gain of about

$1\frac{1}{2}$ pounds of thrust (or 1/300 g) per degree of body deflection was selected for both translational control modes on the basis of practical valve-linkage considerations.



Operation of all three control modes simultaneously became fairly successful after a little practice, but a single, glaring deficiency clearly interfered with natural control. The manner of picking off waist bending required that thigh motion be reserved exclusively for fore-and-aft control, thereby precluding the use of true squatting for up-and-down control. Unfortunately, pure knee flexing turned out to be a highly unnatural substitute for squatting; unless the flyer put his mind to it, he invariably squatted for up-and-down commands, causing a most disconcerting, concomitant, fore-and-aft response. An occasional tendency to become confused in the use of the translational controls can probably be attributed to this cross coupling effect, and it was interesting to note that dead zone (detrimental in the prior experiments) now seemed to be helpful for reorientation after a period of momentary confusion, raising the question of whether some sort of tangible neutrals might be desirable.

It was quite clear that pitch control remained good or perhaps even improved a bit when the flyer became preoccupied with his translational controls, which plainly demonstrated the value of "natural" neuro-muscular mechanisms in this application.

Although very little body motion could be seen, the translational control gains were judged to be far too low, even lower than the rotational gain, and there was a distinct feeling of disharmony between the modes.

THE CURRENT CONFIGURATION AND ITS BEHAVIOR

General

The evolutionary succession of control configurations described in the previous section has led, with increasing success, to the present form, which might be considered a kind of culmination, because it represents a prototype of a truly workable system for spaceman maneuvering. There are, admittedly, questions not yet answered and details remaining to be refined, but the practicality of the concept clearly has been demonstrated.

The simulator is now equipped for study of both proportional and on-off control. The control valve linkage geometries have been modified to eliminate cross coupling between squatting and waist bending, and provision has been made for centering springs and detents on all three controls. The following paragraphs describe and discuss the most recent series of experiments.

A short motion picture illustrating the control modes investigated, and demonstrating operation of the three-degree-of-freedom system in simple, simulated space tasks has been prepared as a part of this report and is available on loan (see reader service cards).

Proportional Control

Mechanical considerations have not permitted any appreciable increase in the system gains over those used in Configuration 4, so the same questions concerning gain and gain harmony remain. It has turned out, however, that the elimination of translational control cross coupling has provided such a dramatic increment in naturalness that the gain problem has lost much of its immediacy; the system, even with its low, inharmonious gains, has become workable.

The scooter as shown in Fig. 5 has been fairly extensively flown in simulated space task maneuvers, and a number of impressions about its flyability under various conditions have been formed:

1) All three modes of control (ankle deflection, squatting, and waist bending) can be handled quite nicely, but with varying degrees of apparent naturalness. The relatively low gains of the translational modes almost certainly contribute to their lower quality, but there is a powerful experimental artifact that must

raise serious doubt about any hasty judgements of control naturalness. This has to do with the sound of the control jets, which is loud, disconcerting, and often downright confusing. Because maneuvering is typically slow and deliberate, the motion cues (visual and proprioceptive) by which a flyer should operate, are weak and easily swamped by strong aural cues. Unfortunately there is a very strong urge, especially in the novice, to try to use the jet noise cues for flying. This can, in fact, be done for very simple maneuvers, but the sounds become hopelessly confusing in complex situations, and the flyer who has begun to rely on them often finds himself in a panic, unable (momentarily) to figure out what to do. It requires a strong effort of will for the novice to ignore the sound and attend only to the proper signals. Once he has learned to do this, however, his flying becomes much more instinctive.

2) Centering springs on the controls are, in general, beneficial; they make it easier for the flyer, especially the novice, to find neutral. Detents, in the form of preloads on the springs, are also useful. A certain amount of care in the selection of spring rates and detent loads must be used, however, lest the flyer's natural coordination of hip and knee flexing in squatting be upset and, more critically, lest the subjective values of system gain be reduced.

It turns out, in this respect, that a flyer's interpretation of gain seems to be based on some over-all feeling of "effort" required to obtain a given response. Thus gain ought really to be expressed in terms of "acceleration per unit of effort," but it is not clear just how a flyer senses accelerations or how he defines "effort." Apparently, "effort" represents some combination of force and displacement, but just what combination is quite unknown. Its mathematical describing function undoubtedly is one in which the relative contributions of force and displacement to the subjective impression of gain vary drastically with the spring rate, ranging from all-displacement at zero spring rate to all-force at infinite spring rate. A determination of this function for the various control modes could become the objective of some interesting additional experimentation.

Comparison of the flying characteristics of the scooter with and without centering springs is of some interest. It turns out that the novice is much more comfortable, and maneuvers more skillfully, with springs, but the experienced flyer apparently does equally well either way, and, in fact, if there is appreciable dead zone in the control system, may actually prefer no springs. Probably, as previously discussed, this is because the expert is able to ignore the sound of small residual jet flows resulting from his imprecision in neutralizing the valves. Such flows, though of negligible effect on maneuvering,* are quite audible, hence difficult for the novice to ignore, and likely to cause him to go through a great deal of unneccesary struggle to eliminate them. Thus he prefers the springs, which permit him to shut off his jets completely simply by relaxing. The expert, on the other hand, tends to be annoyed by the springs because they demand more effort, particularly if there is a large dead zone to be pushed through before the jets come on. This line of thought now returns closely to the previous discussion about the meaning of "effort" in the operation of the control system. The expert's objection to the effort required to manipulate the springs appears to be based not so much on muscular "laziness" — the spring forces (a pound or two) are, after all, far lower than people handle routinely without complaint — as on some sort of "control quickness" factor; in other words, "effort" seems to refer more to subtle difficulties with the response characteristics of the system (including the neuromuscular part). If this is in fact the case, the general study of gain previously suggested becomes all the more intriguing, and possibly quite important to the design of optimum systems.

3) Control power levels required for useful maneuvering are remarkably low. Maximum thrusts and torques typically used on the scooter (although more is available) are about 5 pounds and 15 foot-pounds, respectively which translate to about 2 pounds and 4 foot-pounds in the real spaceflight situation, where the thrusters do not have to move the considerable mass of the scooter. Such low values are certainly significant to the design of a practical system.

On-Off Control

There are two, potential, major advantages to the use of on-off operation in the present application: thruster control may be simpler, and fuel specific impulse may be greater. Thus the flying qualities of on-off control systems are of some importance to the over-all picture.

The simulator was modified for on-off control experimentation by the addition of a solenoid-operated air valve behind each thruster nozzle, and short throw, low force, snap switches at each body motion pickoff point. Nozzles of various diameters were provided for each thruster to permit examination of the effect of thrust level. Views of the scooter as it was thus set up are shown in Fig. 6.

*Of course, in real space operations there could well be a strong economy factor, in which case the fuel wastage accompanying no-spring operation might be decisive.

Initial trials of the on-off system were conducted with thrust levels of $10\frac{1}{2}$ pounds for the translational modes, and a torque level of 15 foot-pounds for the pitch mode. Centering springs and detents as in the proportional control experiments were used, and the "off" zones of the controls were made fairly large. The flyability of this arrangement turned out to be much better than expected, but several deficiences stood out quite clearly. For one, the "off" zones were far too large, giving a subjective impression resembling unduly low gain in the proportional control system. Secondly, there was an annoyingly large hysteresis in the switching arrangement, which created the effect of requiring a positive effort to shut off a thruster once it had been turned on. Because of the flyer's neuro-muscular time lag this put a noticeable lower limit on the minimum duration of a thrust burst (perhaps $\frac{1}{4}$ second), resulting in constant over-controlling and "limit-cycle" type of behavior during attempts at delicate maneuvering. And thirdly, $10\frac{1}{2}$ pounds of thrust was much too high, clearly aggravating the hysteresis problem and essentially precluding precision control. This thrust level also caused a peculiar dynamic instability, characterized by a high frequency (2 cps), limit cycle type of oscillation in the waist-bending mode, whenever the flyer arched back against the spring just to the edge of switch closure. This phenomenon was not particularly debilitating because it occurred only rarely and could be stopped by simply relaxing, but it does illustrate a potential problem with on-off systems that could very well dictate such factors as thruster location, centering spring sizes, and "off" zone minima.

Following these experiments, the "guilty" parameters were readjusted to the levels shown in Table I. Flight with this configuration turned out to be remarkably good. Delicate maneuvers could be made with precision, and the flying, though done in a style noticeably different from that of the proportional control system, was quite natural.

As in the proportional control experimentation, comparison between configurations with and without centering springs revealed significant differences in behavior. As before, springs benefitted the novice more than the expert and called for reduction of the dead zones (in this case the "off" zones). But, unlike the proportional case, springs seemed to be preferred by both expert and novice. A strong tendency toward limit-cycle type of operation without springs is the probable explanation.

Table I

NOMINAL PHYSICAL CHARACTERISTICS

	Ankle	Knee	Waist
Off Zone	$\pm$ $1\frac{1}{4}$ deg	$\pm$ $1\frac{1}{4}$ deg	$\pm$ 1 deg
Friction	Nil	Nil	Nil
Turn-On Torque	$\pm$ 16 in.-lb	$\pm$ 45 in.-lb	$\pm$ 40 in.-lb
On-Off Differential	4 in.-lb	12 in.-lb	18 in.-lb
Detent Torque	$\pm$ 8 in.-lb	$\pm$ 30 in.-lb	Nil
Thruster Effort	$\pm$ 15 ft-lb	$\pm$ $2\frac{1}{2}$ lb	$\pm$ $2\frac{1}{2}$ lb
Mass Scooter & Man	15 Slugs		
Mom. of Inertia Scooter & Man	42 Slug-ft^2		

Although the basic control parameters (thrust, "off" zone size, and control-centering strength) have admittedly not been optimized, on-off control is certainly practical. This is clearly demonstrated in the motion picture, which accompanies this report (see p. 9), and which shows typical, simulated, space-task maneuvering using the on-off control system.

Proportional versus On-Off

Several subjective impressions regarding the comparison of the behavior of on-off and proportional control systems have evolved:

1) The character of the flying of the two systems is clearly different. The proportional system seems to promote simultaneous operation of the various controls with a consequent feeling of continuity and smoothness during complex maneuvers. On-off controlling, on the other hand, seems to be done primarily sequentially, so that

maneuvering becomes a series of discreet operations. (Of course, the actual flight path is smooth and essentially as precise as that of the proportional system.) The feeling of smooth continuity in proportional flying is particularly striking and pleasant immediately after transition from an extended period of practice in on-off control. This may, however, result as much from the character of the jet sounds — which change from a cacaphony of brain stabbing blasts to a modulated hissing — as from actual motion effects.

2) Fast maneuvers are performed more confidently with the porportional system. This undoubtedly stems from the availability of larger thrusts that can be used as "safety margins" to compensate for any misjudgements in speed. With the on-off control, only one level of "braking" is available, and the flyer must therefore be more skillful in his selection of braking points, particularly if he is trying to operate as smoothly as possible. Of course if the maximum proportional thrust is not larger than the on-off value, this conclusion would be invalid, and in fact the proportional flyer might have more trouble with fast maneuvers if "running out" of control power comes as a surprise.

The whole question of the desirability of fast maneuvering is complicated by the fact that velocity is equivalent to fuel increment, and it is therefore desirable from the economy standpoint to keep all motion as slow as possible. On the other hand, factors such as the limits of human patience or the need to get a job done quickly may overbear economy at some point. Thus the parameters that govern fast maneuverability ought eventually to be examined in detail. It is clear, here, that control power is a strong parameter up to a point, but that human factors such as ability to judge and predict, and neuro-muscular lags must enter the picture sooner or later.

On balance, proportional control appears to be generally better than on-off control, but not so much better that some engineering consideration, such as simplicity of thruster actuation, could not specify the use of an on-off system.

PRELIMINARY DESIGN OF PROTOTYPE FLIGHT SYSTEMS

General

Based upon the success of the limited degree of freedom experiments and on a certain amount of optimism about extrapolation to full control, it was decided that some effort should be put on preliminary hardware design to give an indication of what a real flight system might look like. The basic design philosophy was specified essentially as follows. The system must provide complete, natural, and precise spatial control along the lines laid down by the basic "balancing-reflex" concept and by the experimental results gathered to date. It must also be as simple and practical as possible for use by an astronaut in a spacecraft environment, such as that of Gemini.

Thruster Considerations

Because propulsion is fundamental to any system of the kind sought, it looked as though the design might have to stand or fall with the thrusters. Experience had certainly shown that compressed gas devices are impractical from both the efficiency and controllability standpoints. Solid propellant rockets were clearly out, and the more esoteric forms of liquid rocket seemed much too complex and expensive for this application. This apparently left liquid monopropellant (most probably hydrogen peroxide or hydrazine) rockets as the only alternative. No extensive survey of the rocket industry was conducted, but it turned out that at least one company makes a small, monopropellant hydrazine rocket (Ref. 13) that looks to be ideal for the desired application; it is simple, reliable, efficient, long lasting, easily controllable, and throttlable over a wide range with minimal loss. The preliminary design thinking, therefore, has been based more or less upon this unit.

The Designs

The layout of the complete primary system — which, incidentally, is the configuration upon which the frontispiece artist's conception is based — is shown in Fig. 7. The separate modes of control that it provides, and the respective thruster responses, are shown schematically in Fig. 8.

It will be noted that only five degrees of freedom are included, lateral translation being omitted. The rationale behind this (more thoroughly discussed in the following Questions and Speculations Section) is, basically, that lateral translation would be needed only for close-in work and in small amounts, and therefore could be adequately effected by use of a "backing and filling" technique involving yaw and fore-and-aft control. This idea is admittedly a speculation that would have to be demonstrated, but in any case lateral translation could be added to the design at a certain cost in complexity.

An interesting feature of the design shown is that all thruster valving functions are carried out in the compact mechanism between the feet, and that, essentially, the feet become the agents for all control. This arrangement, besides being appealingly simple, eliminates some of the control harmony problems that ensue from picking off body deflections higher up. It is anticipated that the device would be made foldable for compact stowage.

One of the design ground rules was, as stated, that a configuration should offer "complete" control, which, in fact, the primary design does. But it became apparent that an extremely simple device to complement the existing Air Force-NASA backpack "AMU" could be designed if only three control functions were assigned to the legs. This intriguing device is described here, although it is not germain to the central theme of the present work.

The layout and control pickoff details of this "AMU auxiliary" system are shown in Fig. 9. This device is intended to be connected to the backpack by a flexible cable (electric if on-off type control is used), with no rigid connection to the upper legs or body being required. In operation, the backpack would be counted upon to provide stabilization in pitch and yaw (with manual override) by means of its gyros. The legs, acting through the feet, would provide the control of roll rotation and fore-and-aft, up-and-down translation. Thus a man presumably could work nicely in proximity to some object without using his hands for control.

QUESTIONS AND SPECULATIONS

The experimentation and preliminary design thinking carried out to date have proved a basic concept and taken a large step toward a practical device. But there remains a number of possibly crucial, unanswered questions. Some speculative discussion of these follows.

Are More Than Three Degrees of Control Freedom Practical?

This is the crucial question, and it is not likely to be answered with any finality until a complete system can be tried, either in flight or in a complete-motion simulator. There are some encouraging signs, however. For instance, there is the demonstrated naturalness of the pitch and roll rotational control modes in one-g and "zero-g" environments, and there is Zimmerman's one-g demonstration that the two modes can be combined without upsetting their instinctive operation. There is also the nice analogy between the suggested yaw control mechanism and the established pitch and roll control mechanisms (see Fig. 8). These three items lead easily to the speculation that control of all rotations simultaneously can be just as natural and instinctive as control of one alone. If this can indeed be shown, there is room for a good deal of optimism that control of at least five degrees of freedom will be little, if any, harder than the presently demonstrated three. Thus it seems that the crucial experiments for the near future must involve demonstration of the suggested yaw control mechanism, and examination of the simultaneous use of the three rotational control modes. Present plans at Grumman include these items.

Are Six Degrees of Control Freedom Necessary?

This question can be asked in connection with ideas not only of human capacity, but of mechanical complexity. Under the assumption that complete control of rotation is vital to the performance of space tasks and is relatively easy to accomplish, the question becomes, "Are three degrees of translational control freedom necessary?" At one point during the experimentation described in this report, the question was phrased, "Could, for instance, control of vertical translation be successfully eliminated?" The answer turned out (not too unexpectedly) to be an unqualified "No;" the mechanical process of "backing and filling," or "tacking," (using pitch rotation), to effect a change in vertical position proved to be unacceptably clumsy. But the same process using yaw rotation to effect a lateral translation might not be at all clumsy, because yawing (as in body twisting) is quick and easy, and requires little space. This philosophy has, in fact, dominated the preliminary design thinking to date, and consequently provision for direct control of lateral translation has not been included (see previous section). Definite proof of the concept must be obtained, however, before any serious, detailed designing of a prototype system can proceed. Planning at Grumman includes early experimentation directed toward this objective.

What Are the Optimum Control System Gains?

Although our thinking has dwelt at length on system gain and its meaning as an important control parameter, little experimentation, specifically aimed at interpreting and quantifying gain, has been possible because of the mechanical difficulty of varying the appropriate parameters. The use of small, liquid monopropellant rockets for simulator propulsion, however, should largely remove this obstacle and permit comprehensive, quantitative, research on gain. Present plans at Grumman call for this, but not before certain demonstration-type experiments (as previously discussed) have been completed; existing gain values, though not optimum, are felt to be adequate for a workable prototype control system.

Does a Space Suit Interfere?

One of the principal artifacts of space suit technology today is stiffness. Therefore, any activity of a spaceman that requires extensive flexing of his body must be looked at askance, and it is only natural that doubt should arise in this respect concerning a control system that requires flexing of the hips, knees, and ankles. The present experimentation has shown, however, that the gains preferred in this system are so high that there is very little visible flexing of the body, even during spirited maneuvering. The speculation here, therefore, is that the natural, foot and leg control concept, far from being incompatible with space suit operations, is in fact particularly appropriate for them.

Of course, there always remains the problem of donning, doffing, and stowage of the flight gear, but this would appear, as the prototype is presently conceived, to be no worse than, and perhaps better than, the problems encountered with currently operational devices.

Can the Rocket Exhaust Be Dangerous?

This is a complicated question because it involves considerations of the placement of the control thrusters, the nature of the rocket exhaust, and the probable extent of the activity of a spaceman's arms (the only items of any concern in most configurations). The real danger is probably not to the spaceman's body directly, but to the space suit, which obviously could not stand to have a hole burned in it. If hydrazine rockets are used — and these certainly appear to be appropriate for this application — the rocket exhaust temperature can be brought down to reasonably safe limits (500°F) without a prohibitive loss of fuel-specific-impulse (Ref. 12). If new space suit material developments — such as that recently announced by the Air Force, in which a cloth is made of fine, superalloy wires — raise the acceptable exhaust temperatures, then the fuel specific impulse can be raised appropriately. As far as danger to other objects in space is concerned, the problem primarily involves heat effects and surface contamination by the exhaust material. The exhaust heat would be a problem only if a rocket nozzle got very close to a susceptible object for an appreciable length of time (not highly likely), and in this situation the same considerations as for the space suit material would apply. Clearly, there could be space items that could not tolerate a 500°F gas stream even briefly, and in the vicinity of these the spaceman would just have to be extremely careful.

Contamination of a cold surface by condensation of the decomposition products of hydrazine (ammonia and water) certainly could occur. The extent to which this is debilitating, however, would depend on the function of the item "sprayed." In any case, one would expect that both ammonia and water would eventually sublime or evaporate in a hard vacuum.

What About System Safety?

Two kinds of unwelcome system failures are conceivable: one in which the system dies, leaving the spaceman stranded, and one in which the system goes berserk. Of course, the latter would usually lead also to the former.

For the stranding situation, one can think in terms of a simple, emergency backup system (such as the present "space gun"), or in terms of retrieval of the stranded spaceman by his buddy in the mother vehicle. A certain amount of training in the use of a space gun could be required, however, since the spaceman might well be left with a rotation that he would have to get rid of before he could attempt to return to his vehicle.

For the berserk-system case, one thinks primarily of automatic and manual system cutoffs. A rotation cutoff would most likely have to be automatic, because very nasty spin rates can be built up in fairly short times. It should be possible to devise some sort of rotation sensing mechanism, perhaps based on centrifugal or coriolus effects, which would respond to the emergency but not to ordinary operations. Translation cutoff could probably be done manually.

SUMMARY OF MAJOR CONCLUSIONS

1. The basic concept of precise, hands-free control of spaceman maneuvering by exploitation of instinctive muscular responses of the feet and legs is practical.

2. Accurate, natural control of gravity-free motion in a plane has been demonstrated.

3. A control system should include separate and uncoupled control of the individual degrees of freedom, but control of all six may not be necessary.

4. Ankle deflection for pitch control, differential foot lifting for roll control, squatting for vertical control, and waist bending for fore-and-aft control are instinctive responses.

5. Control mode gains (acceleration per unit of body deflection) should be high, resulting in little or no body flexure noticeable to an observer.

6. Both proportional and on-off control are practical. Proportional control is slightly preferable to the flyer.

7. Mild centering devices on the control pickoffs are generally desirable, but not absolutely necessary.

OUTLINE FOR FUTURE ACTION

The Grumman Aircraft Engineering Corporation believes that future effort in developing the spaceman maneuvering concept should proceed along three basic lines, if possible concurrently, as follows:

I. Demonstrate, in stepwise fashion, using simulators of varying degrees of sophistication, components of the complete control configuration.

   A. Demonstrate the yaw control concept. This would be carried out on a single-degree-of-freedom, rotational simulator now being constructed at Grumman.

   B. Examine the hypothesis that lateral control can be eliminated. This work would be done in the Grumman zero-g simulation facility on a special scooter to be developed.

   C. Demonstrate that simultaneous roll, pitch, and yaw control can be done instinctively. This would be carried out on a special gimbal attachment to either the rotational device of item I.A or the scooter of item I.B.

II. Design, construct, and test (on simulators and in aircraft) one or more prototype flight systems.

   A. Complete the preliminary and detailed design and development work on a 5-degree-of-freedom "pogo stick" configuration, as described in the Preliminary Design of Prototype Flight Systems Section.

   B. Construct a three-rotational-degrees-of-freedom-only version of the system and perform tests necessary for man-rating it.

   C. Demonstrate the system in parabolic flight.

   D. Add the translational degrees of freedom to the system and demonstrate on a six-degree-of-freedom simulator and/or in flight.

III. Perform research leading to the establishment of optima for several system parameters.

A. Modify the Grumman zero-g simulators (scooters) for propulsion by hydrazine or hydrogen peroxide monopropellant rockets.

B. Examine in detail the effects of system gains, spring rates, detent forces, dead zones, maximum thrusts, etc. on flyability.

C. Examine the concept of "gain" in terms of its meaning to the flyer, as discussed in a previous section of this report.

REFERENCES

1. Zimmerman, C. H., Hill, P. R., and Kennedy, T. L., Preliminary Experimental Investigation of the Flight of a Person Supported by a Jet Thrust Device Attached to his Feet, NACA Research Memorandum L52D10, January 1953.

2. Gill, W. J., Summary Report — Airborne Personnel Platform, Hiller Aircraft Report No. ARD-236, Contract No. Nonr 1357(00), June 1959.

3. Townsend, M. W., Jr., Stability and Control of Unducted Stand-On Helicopters, Preliminary Theoretical and Flight Test Results Report No. 404, Contract DA 44-177-TC-392, Dept. Aero. Engr., Princeton University, November 1957.

4. Hill, P. R., and Kennedy, T. L., Flight Test of a Man Standing on a Platform Supported by a Teetering Rotor, NACA Research Memorandum L54B12a, March 1954.

5. Parlett, L. P., Hovering Flight Investigation of Two Methods of Controlling a Man-Carrying Ducted-Fan Vehicle of the Flying-Platform Type, NASA Technical Note D-841, June 1961.

6. Aviation Week and Space Technology, November 16, 1964, pp. 69-70.

7. Aviation Week and Space Technology, August 15, 1966, p. 98 and front cover.

8. Thomas, D. F. Jr.,"'Jet Shoe' Extravehicular Activity Device," Proceedings of the National Conference on Space Maintenance and Extra-Vehicular Activities, Orlando, Florida, March 1-3, 1966, p. 3.1.8.

9. Keller, T., and O'Hagan, J. T., "Vehicular Control Using the Human Balancing Reflex," presented at AIAA Simulation for Aerospace Flight Conference, August 26- 1963, Columbus, Ohio; also Grumman Research Department orandum RM-220J, August 1963.

10. Keller, T., O'Hagan, J., and Weston, R., A Study of the Mechanics of Human Balancing for Potential Application to the Control of Vehicles Part I, Initial Investigation of Vertical Balancing in Earth Gravity, Grumman Research Department Memorandum RM-299, October 1965.

11. Weston, R., Breul, H., O'Hagan, J., and Gardner, G., Hands-Free, Precision Control for Small Hovering Vehicles - A Flying Qualities Study, Grumman Research Department Report RE-276 January 1967.

12. Breul, H., Seckel, E., Weston, R., Suh, S., and Keller, T., A Study of the Mechanics of Human Balancing for Potential Application to the Control of Vehicles Part II, Toward a Mathematical Model of Vertical Balancing in Earth Gravity. Grumman Research Department Report, to be published.

13. Final Report Low Temperature Monopropellant Hydrazine Jet Gun Thrust Chamber Assembly, 66-R-71, Rocket Research Corporation, Seattle Washington.

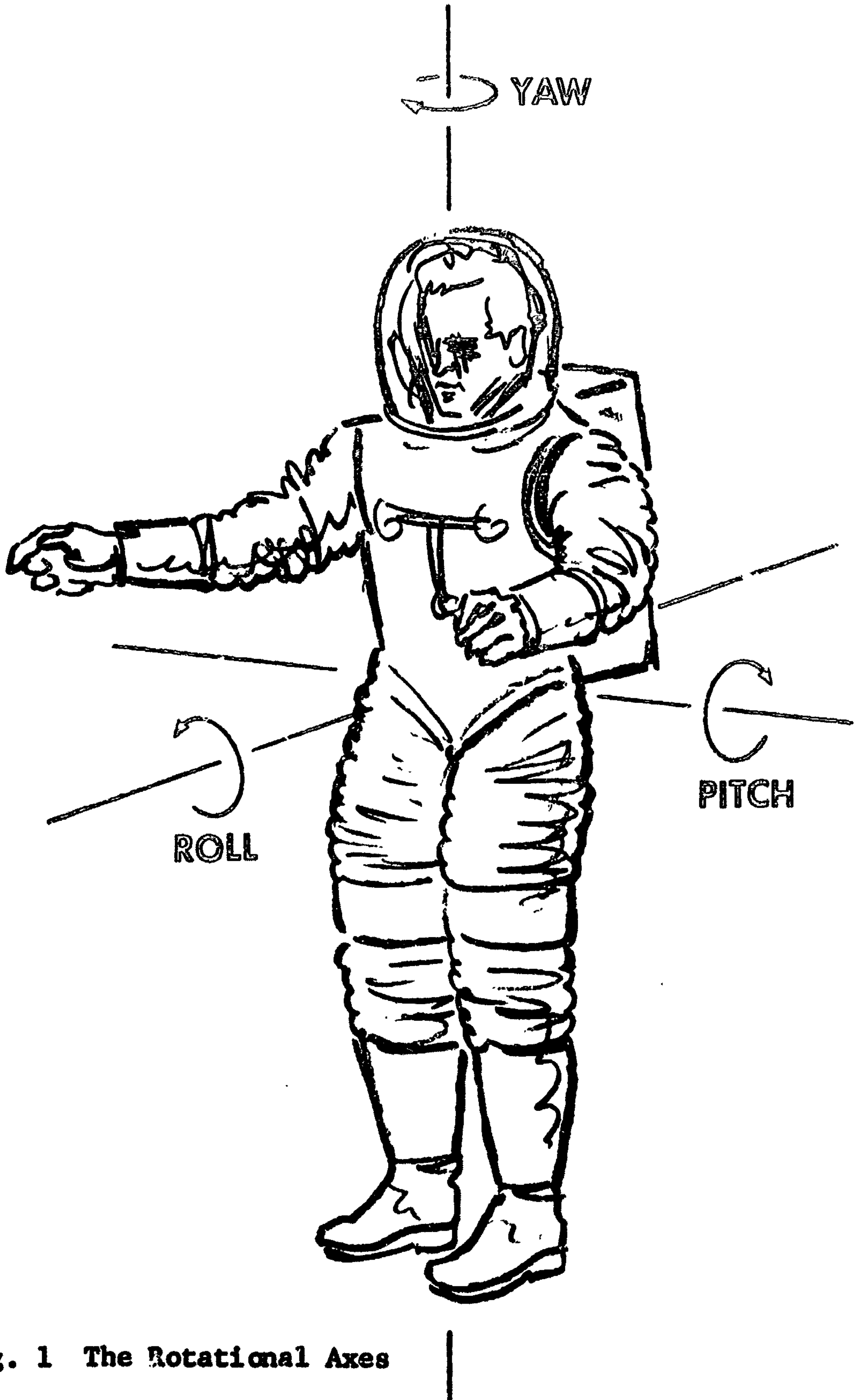


Fig. 1 The Rotational Axes

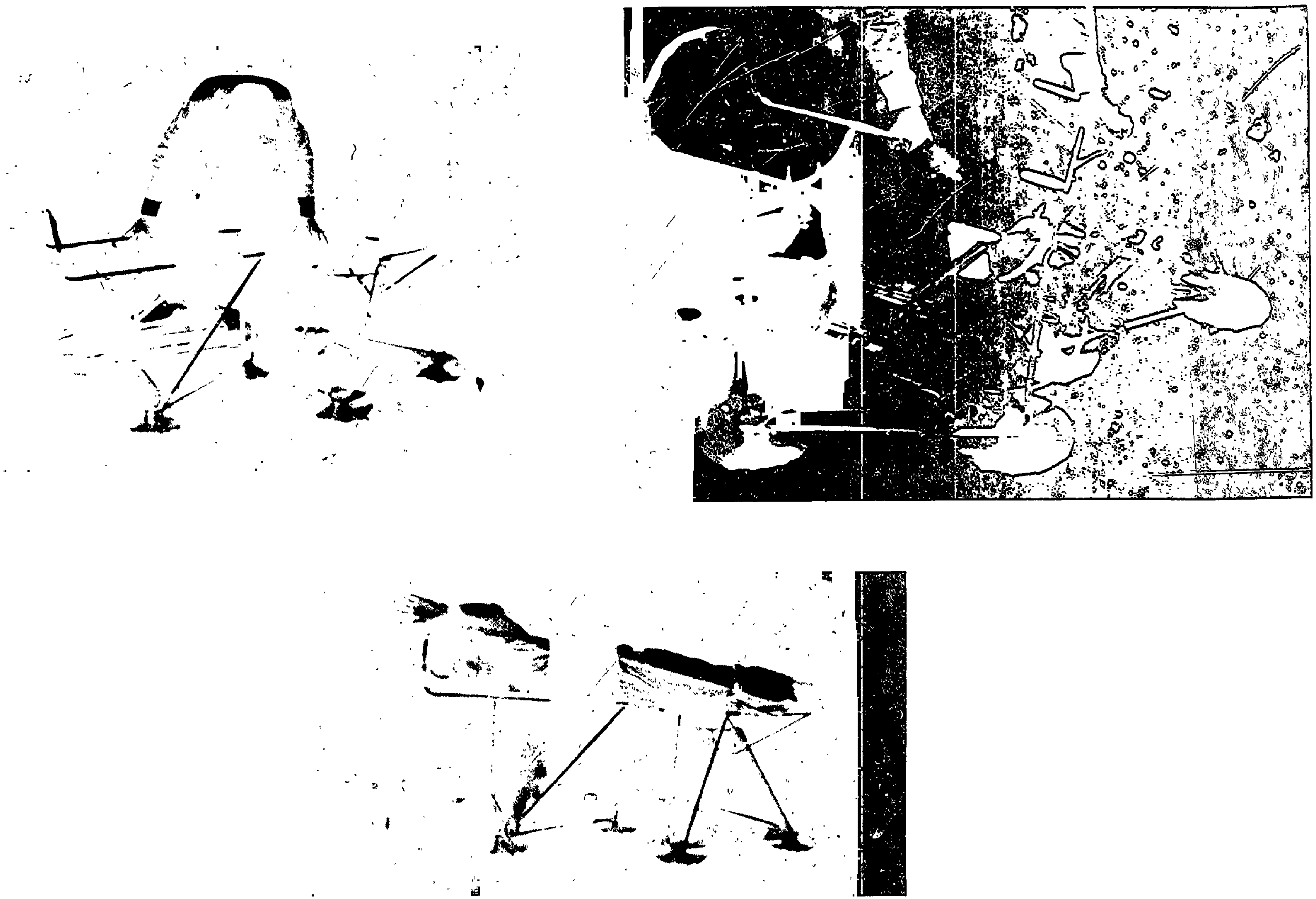


Fig. 2 The Basic Scooter

Fig. 3 Ankle Pivot and Thruster Arrangement for Configuration 2

Fig. 4 One-g Simulator as Modified for "Zero-g" Trials

Note: Screw-Jack Propelled Carriage at Right Accelerates Back and Forth in Response to Ankle Deflections

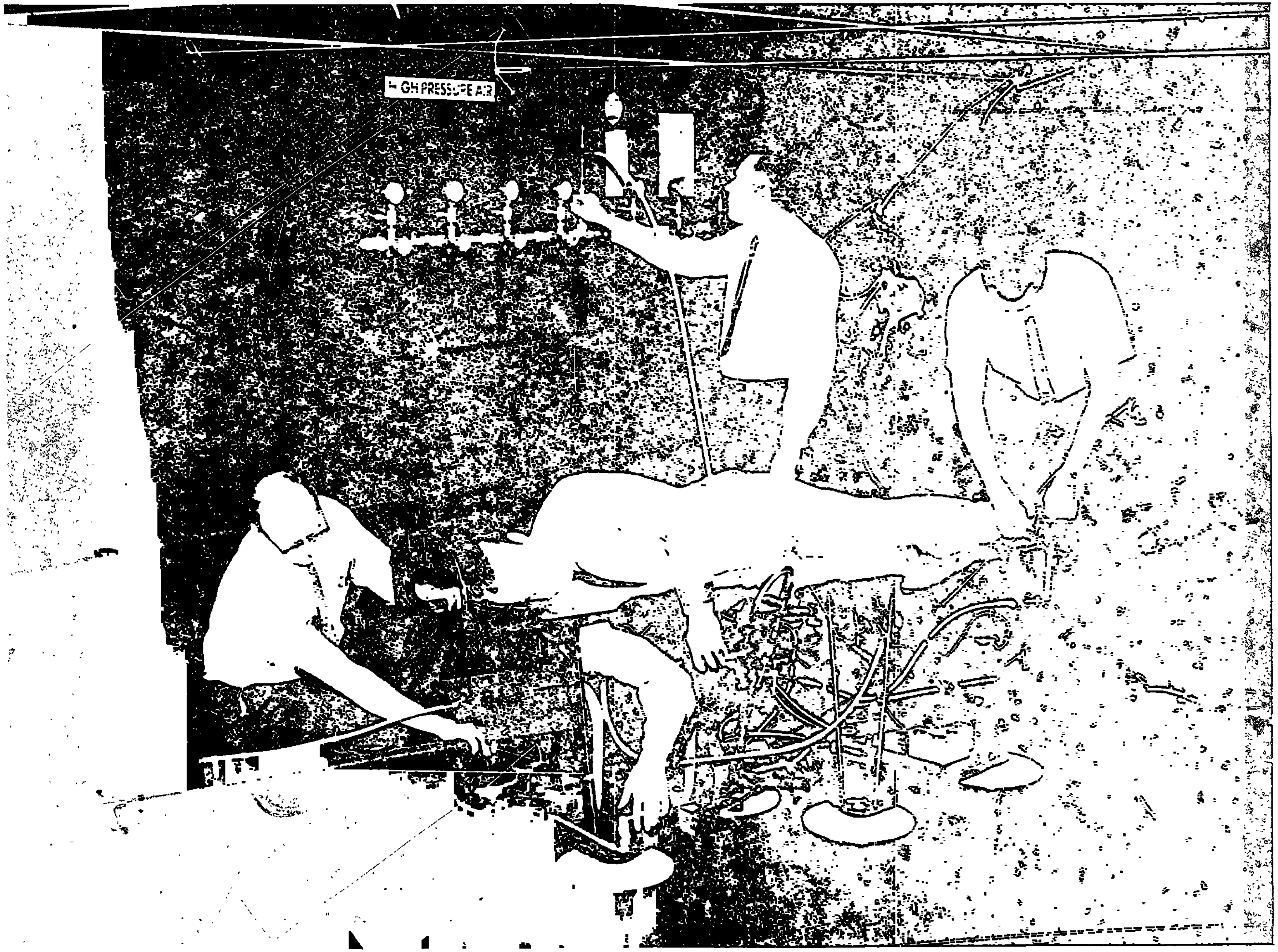


Fig. 5 The Scooter Arranged for Proportional Control

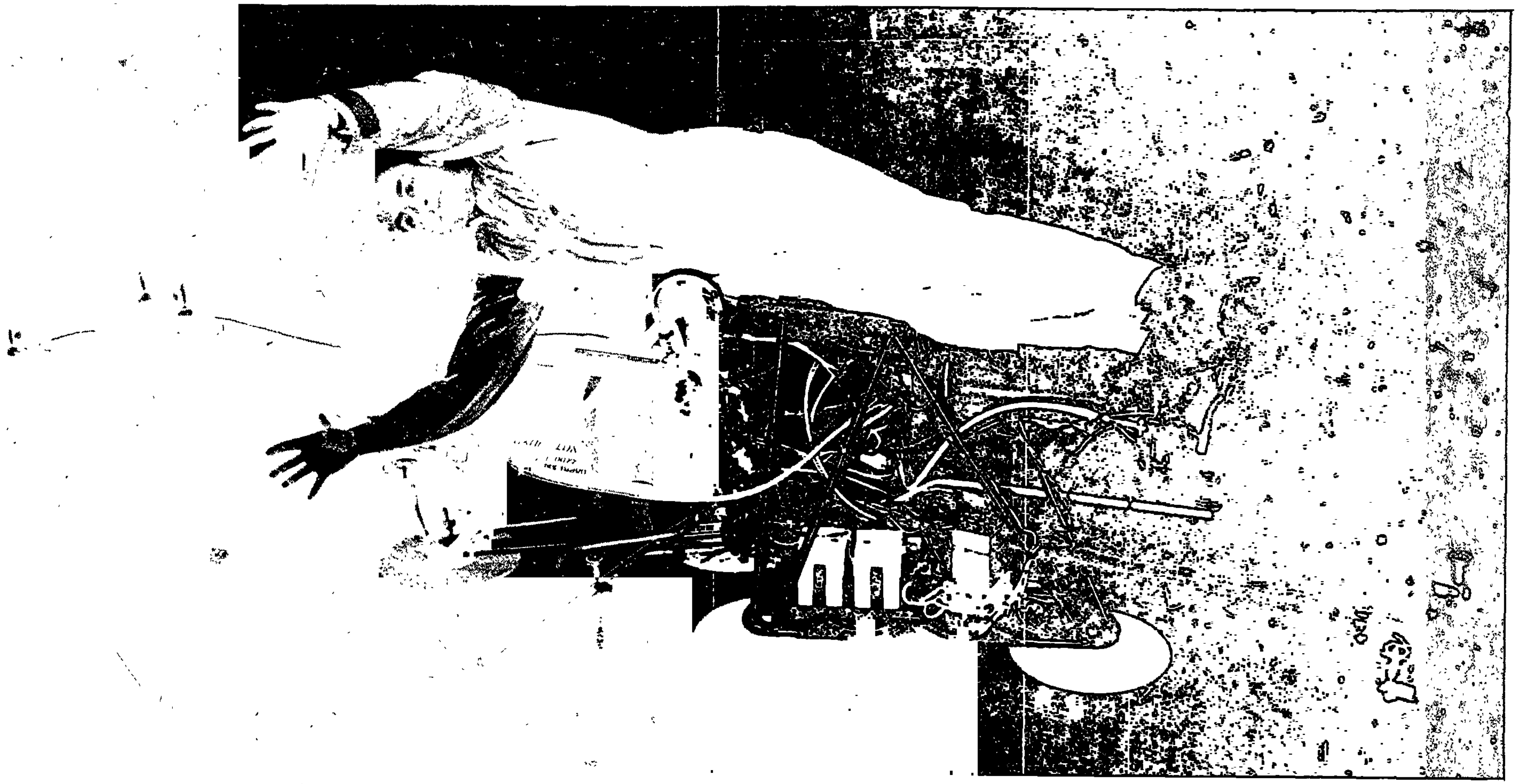
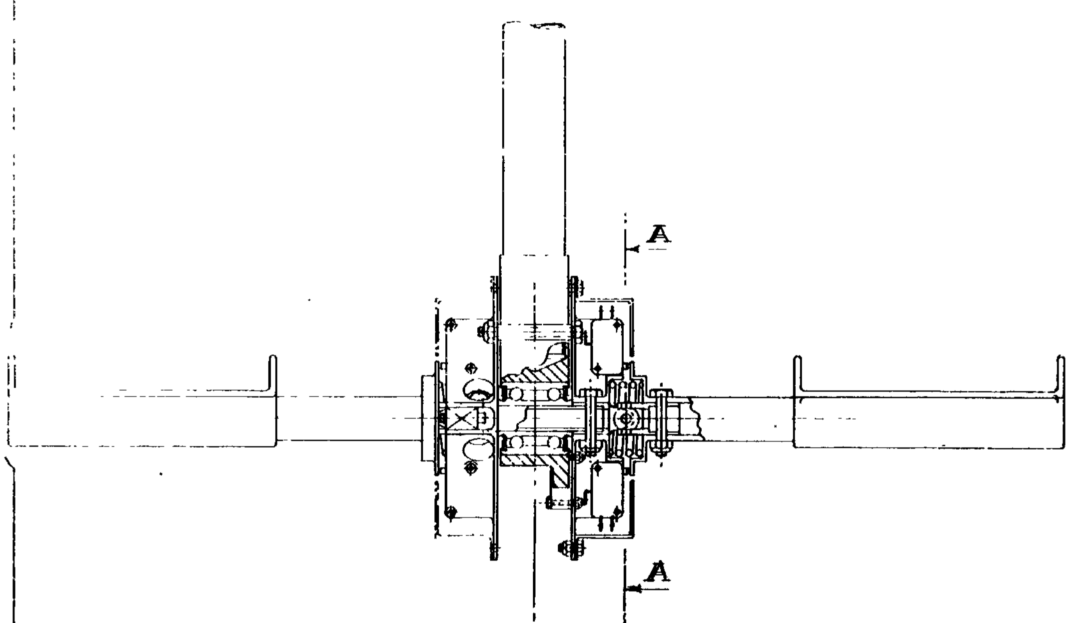


Fig. 6 The Scooter in Its Final Configuration

MANEUVER	PEDALS	JETS
ROLL LEFT	L.H. UP - R.H. DN	1-7
ROLL RIGHT	L.H. DN - R.H. UP	3-5
PITCH UP	TOES DOWN	4-8-9
PITCH DOWN	TOES UP	2-6-10
YAW LEFT	L.H. BACK - R.H. FWD	4-6
YAW RIGHT	L.H. FWD - R.H. BACK	2-8
TRANSLATE FORWARD	L.H. FWD - R.H. FWD	2-6
TRANSLATE BACKWARD	L.H. BACK - R.H. BACK	4-8
TRANSLATE UPWARD	L.H. DWN - R.H. DWN	3-7
TRANSLATE DOWNWARD	L.H. UP R.H. UP	1-5



DETAIL 'B'
(FULL SCALE)

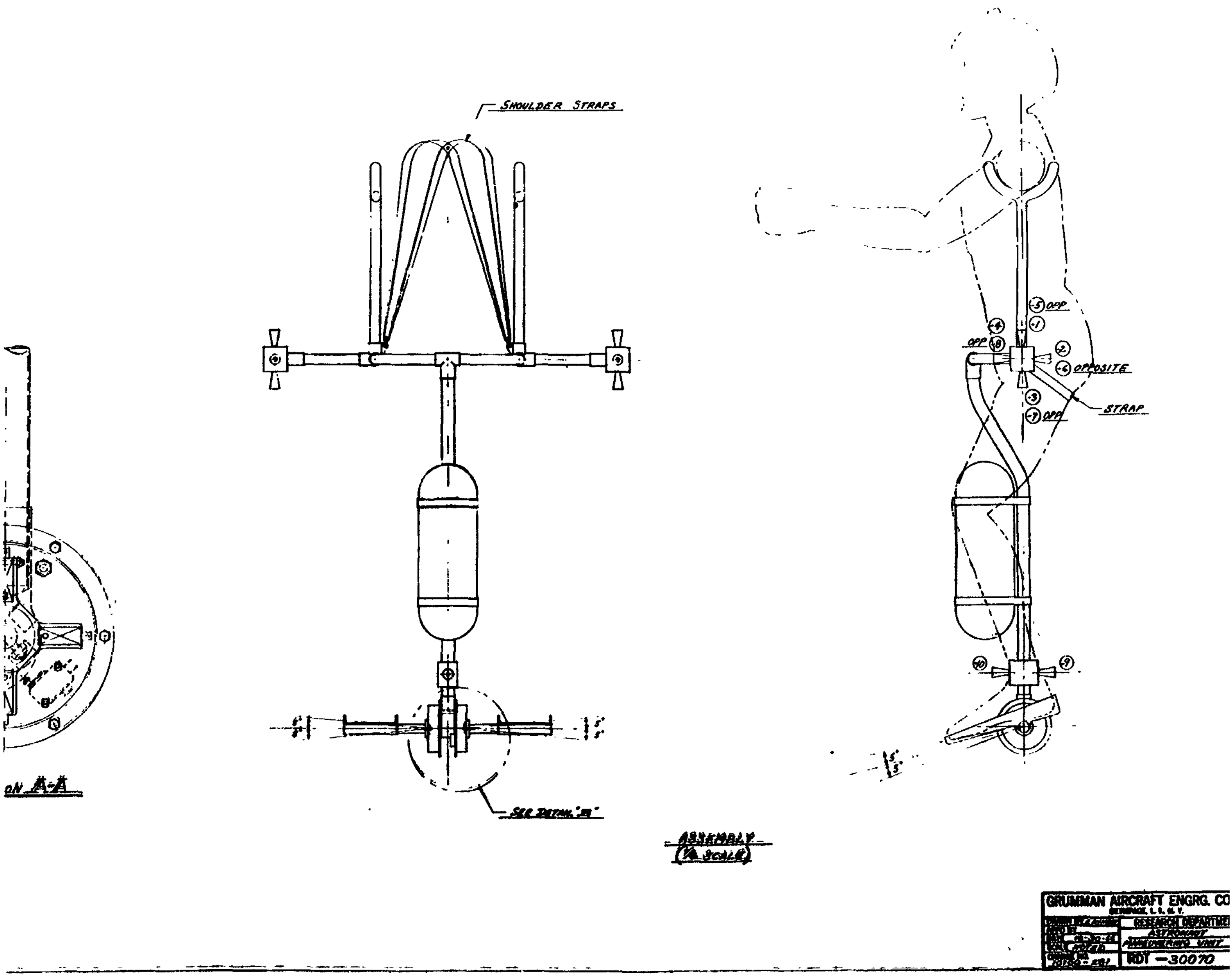


Fig. 7 The "Complete" Prototype

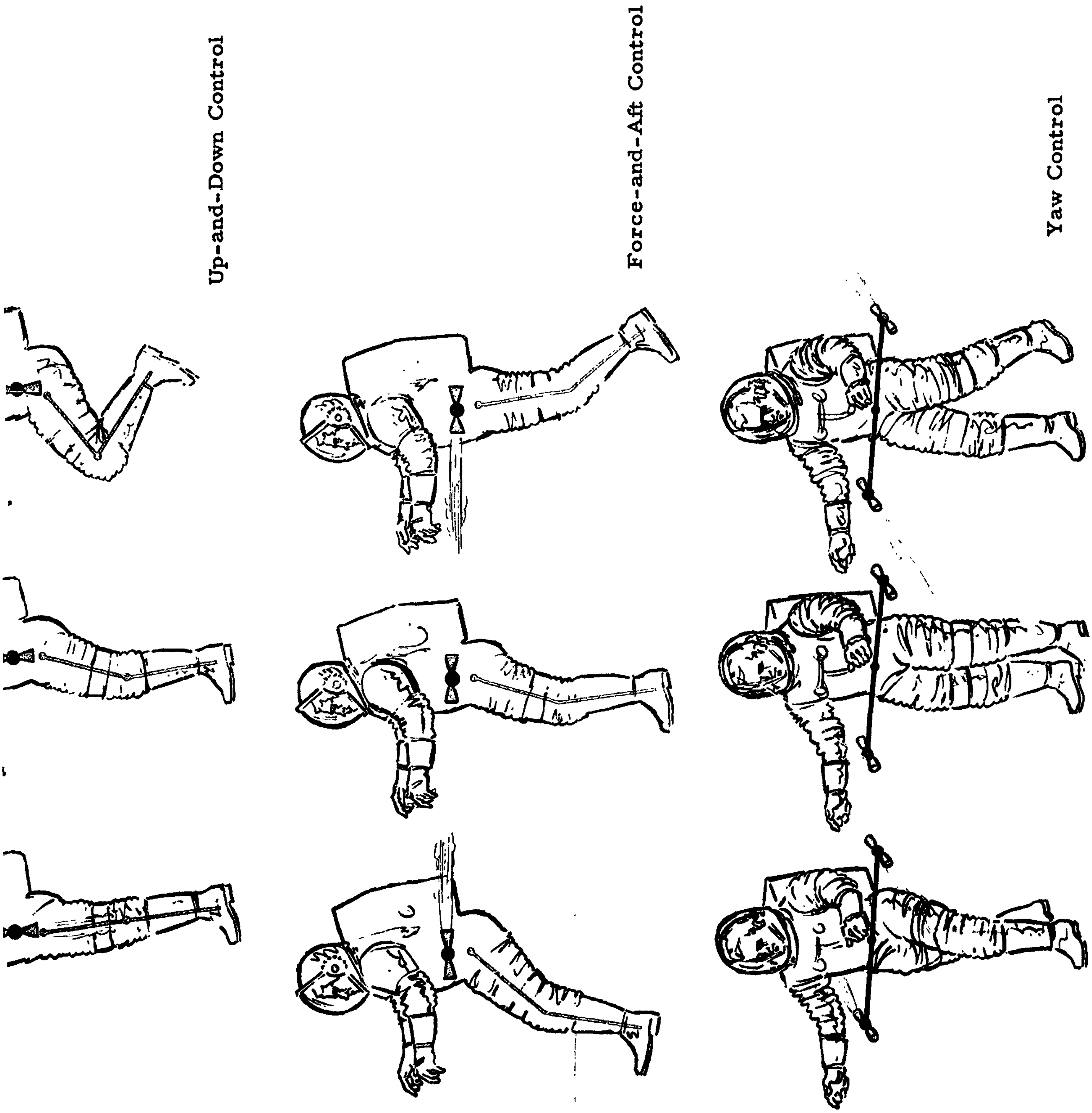


Fig. 8 The Control Modes of the "Complete" Prototype.
Note: The body motions shown are greatly exaggerated.

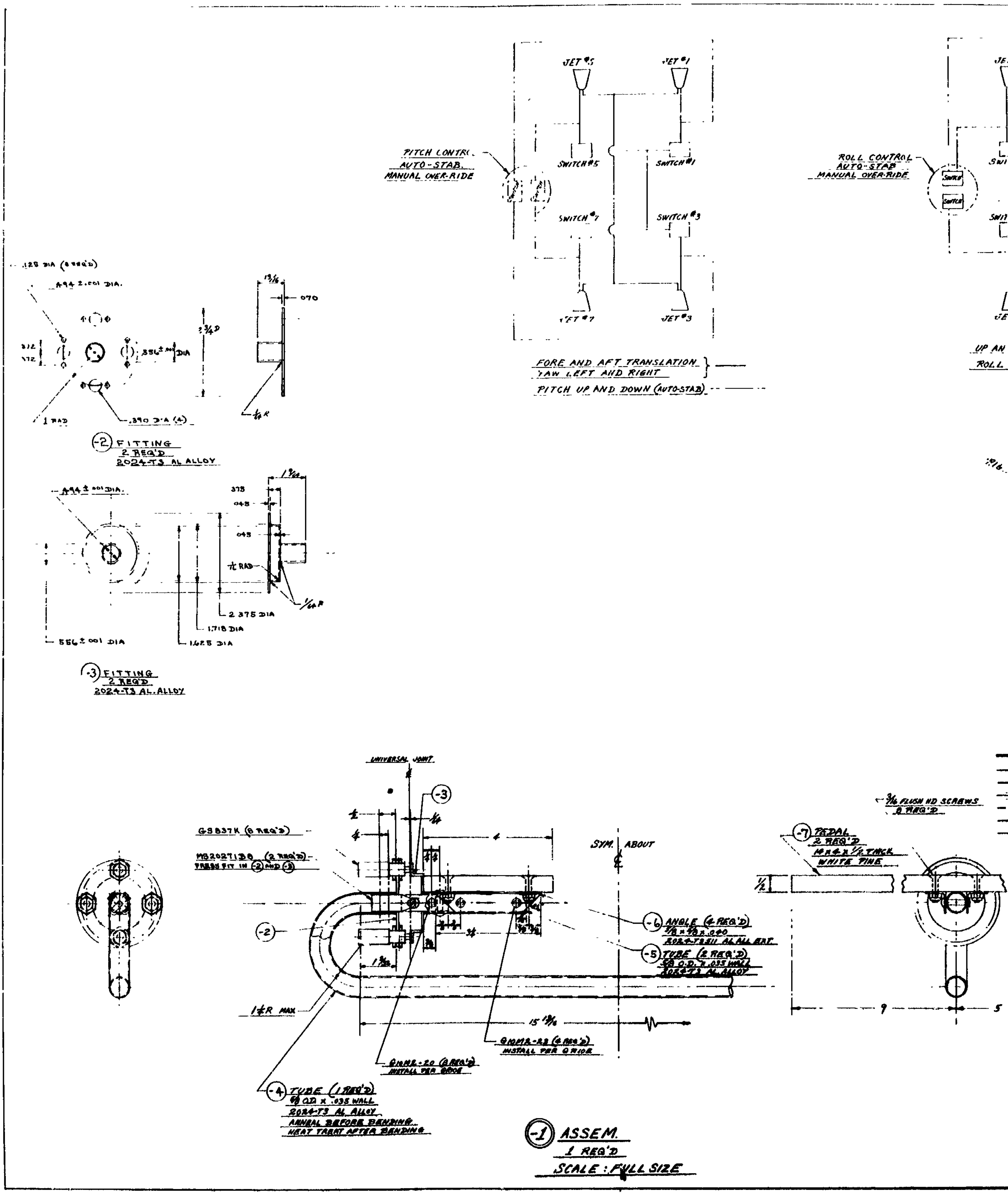
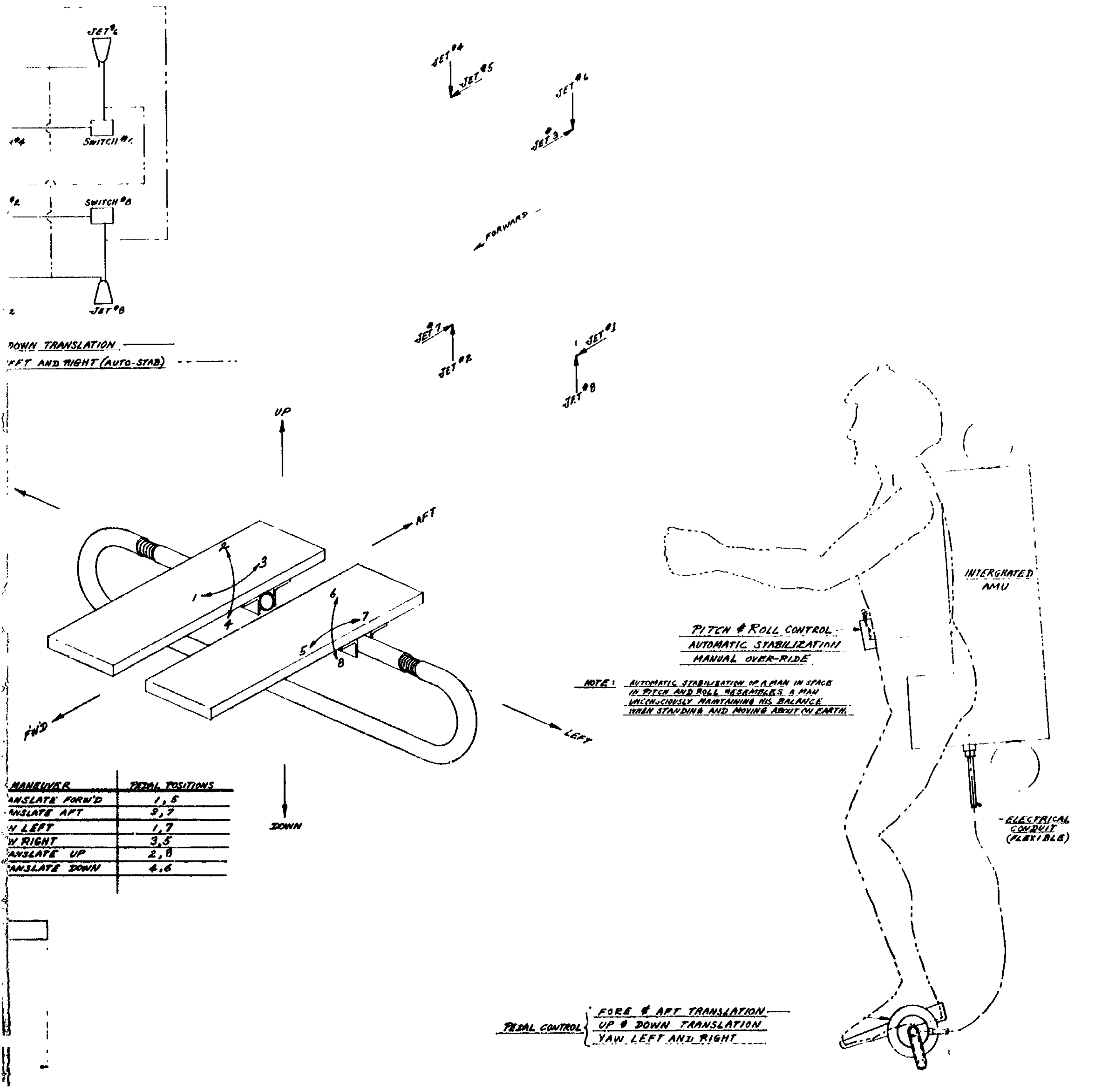


Fig. 9 The "AMU - Auxiliary" Prototype



MANEUVER	PEDAL POSITIONS
ANSLATE FORW'D	1,5
ANSLATE AFT	3,7
W LEFT	1,7
W RIGHT	3,5
ANSLATE UP	2,8
ANSLATE DOWN	4,6

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APPENDIX

THE ADVANTAGES AND POTENTIAL APPLICATIONS OF THE BALANCING-REFLEX-FOR-VEHICULAR-CONTROL CONCEPT (ABSTRACTED FROM REF. 9)

Examples of human controlled mechanisms in which the feet assume portions of the control function abound: automobiles, airplanes, and musical instruments, for example. But almost never is primary control of a process given over entirely to the feet though there may be a clearly obvious advantage in having the hands free for other tasks. The reason for this probably lies in the relatively gross nature of typical neuro-muscular behavior of the feet, with the attendant difficulty of training them for a delicate task. But if the feet and legs are already highly trained for the task, in fact so highly trained that the necessary delicate responses have become reflexes, they should be able not only to do the job adequately, but to do it with practically no training and very little demand on the higher neural centers. Allowing such a function to assume some primary control duty, then, should free the hands and mind for other primary duties and thereby make the overall system more flexible, more capable, and/or more economical. Human balancing turns out to be the desired sort of function. In cases where we need to stabilize and maneuver a vehicle with reference to a gravity (acceleration) vector, and where we can conveniently move the vehicle so as to accelerate a standing pilot in a manner appropriate to his foot movements, the balancing reflex is suitable for the complete control function. There are several classes of vehicles which fall into this category and which conceivably could benefit by adoption of this technique.

Perhaps the largest operational class of vehicles for which the balancing reflex might be used to advantage comprises the terrestrial, airborne machines whose principal duties involve extended periods of hovering or very slow flight at low altitudes. Typical usage of this class seems to involve, besides control of the vehicle, special crew duties demanding precise use of the hands and close attention; in military combat vehicles, for instance: the firing of weapons, operation of reconnaissance devices, etc.; in specialized vehicles such as flying cranes: the operation of hoists and other functional devices; in small, one-man vehicles for operations in places of poor accessibility: the performance of the particular special duties.

Another class of operation to be considered is space transportation. Here, there are certain specialized jobs for which the balancing reflex may show a clear-cut mechanistic advantage in addition to its hands-free characteristic. For instance, current thinking on the free-floating space worker seems to be dominated by the "Buck Rogers" concept, in which the spaceman is provided with a "rocket belt" strapped to his shoulders. Now this concept does indeed make use of natural body movements for control of rotation just as the balancing reflex does, but these movements, involving the trunk and legs, are perforce relatively clumsy and gross. Furthermore, because the torso is not very flexible and the backpack is close to the body's center of gravity, the maximum control power (angular acceleration per unit of thrust) obtainable is relatively small. By contrast, the balancing reflex concept — in this case jet nozzles fixed to the feet — offers a high degree of control finesse and large control power, presumably desirable properties for orbital assembly or repair work. Another example, though less clear-cut, of space flight application might be the human-controlled, final or "hovering" stage of lunar landing; the vehicular behavior in this operation cuuld be so unusual as to be more suited to control by the balancing reflex than by conventional means. Of course, the question of a standing human's vulnerability to landing shock must be raised in this connection.

A third category of potential application comprises various sorts of ground-borne vehicles, either rolling or floating (air cushion). Again the primary advantage would be the hands-free operation, for example in individual transportation for postmen, messengers, stock chasers, and the like. There is also a basic and important engineering advantage connected with small vehicles of the air cushion (and the flying) type; the control system can be absurdly simple.